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A note on the nonlinear reflection of laser radiation from a dense plasma

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Abstract: A high power laser radiation propagating in a dense plasma, suffers total reflection from the critical layer ($\omega_p = \omega$). At the critical layer the electric field of the laser is considerably high and the plasma experiences a strong ponderomotive force. This force causes considerable redistribution of the plasma density and hence the phenomenon of reflection is greatly modified. For a typical CO_2 laser, the nonlinear effects are prominant at power densities $\sim 10^{13}$ Watts/cm^2.

1. Introduction

A laser beam propagating in the direction of density gradient in a plasma is reflected back from the layer of critical electron density (Ginzburg 1970). In the vicinity of the critical layer, the scale length of intensity variation is small and the amplitude of the electric field is large Consequently at high powers, the electrons experience a strong ponderomotive force (Sodha *et al* 1976, Hora 1969) and density profile should be greatly modified (due to the depletion of plasma from the regions of high intensity). The profile modification takes place on a time scale $\tau_p \approx \lambda_{eff}/C_s$ where C_s is the ion sound speed and λ_{eff} is the intensity scale length. For typical laser produced plasmas $\tau_p \approx 10^{-10}$ sec This value of τ_p, in many cases, is smaller than the duration of the laser pulse The modified density profile should influence the intensity profile of the laser and must affect the parametric process (both the convective and absolute instabilities) a great deal (Liu and Kaw 1976) In this note we have obtained the self consistent modification in the plasma density and the laser intensity on a time scale greater than τ_p.

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We consider the propagation of a plane polarised ($\mathbf{E}\|y$) laser beam in the direction of the density gradient in a plasma characterized by a linear density profile

$$n = n_0(1+Z/L), \tag{1}$$

where n_0 is the critical electron density and L the density scale length. At low powers the electric field of the laser is an Airy function $A_i\ (z/\lambda)$ where $\lambda = (C^2L/\omega^2)^{1/3}$. At high powers, the electrons should experience a strong ponderomotive force and the modified electron density profile could be written as (Soda *et al* 1976)

$$n' = n_0'(1+z/L)\exp(-\alpha EE^*), \tag{2}$$

where

$$\alpha = e^2/8m\omega^2T,$$

is the nonlinearity parameter,

$$n_0' = \frac{n_0 \int_{-L}^{u} \left(1+\dfrac{z}{L}\right) dz}{\int_{-L}^{u} \left(1+\dfrac{z}{L}\right) \exp(-\alpha EE^*)dz} \tag{2a}$$

is the normalization constant and u is the upper boundary of the Plasma T is electron temperature in eV.

In writing equation (2a) we have assumed that the total number of electrons in the plasma are conserved. In most of the situations the transverse size of the laser beam is finite ($= r_0$) and the plasma may be redistributed in the transverse direction giving rise to the above mentioned expression for electron density with $n_0' = n_0$ In other cases also n_0' is close to n_0.

The electric field of the laser is governed by the wave equation

$$\frac{d^2E}{dZ^2} + \frac{\omega^2}{c^2}(1-4\pi n'e^2/m\omega^2)E = 0. \tag{3}$$

Introducing a new variable $\xi = Z/\lambda$, we obtain

$$\frac{d^2E}{d\xi^2} - \xi E + ((\omega L/c)^{2/3}+\xi)(1-\exp-\alpha EE^*)E = 0. \tag{4}$$

Separating the real and imaginary parts of equation (4) one gets

$$\frac{d^2E_r}{d\xi^2} - \xi E_r + ((\omega L/c)^{2/3}+\xi)(1-\exp-\alpha(E_r^2+E_i^2))E_r = 0. \tag{5a}$$

$$\frac{d^2E_i}{d\xi^2} - \xi E_i + ((\omega L/c)^{2/3}+\xi)(1-\exp-\alpha(E_r^2+E_i^2))E_i = 0. \tag{5b}$$

Multiplying equation (5a) by E_i and (5b) by E_r and subtracting the latter equation from the former, we obtain

$$\frac{d}{d\xi}\left(E_i\frac{dE_r}{d\xi}-E_r\frac{dE_i}{d\xi}\right)=0. \tag{6}$$

However, as $\xi\to\infty$, E_r and $E_i\to 0$, hence.

$$E_i\frac{dE_r}{d\xi}-E_r\frac{dE_i}{d\xi}=0$$

or

$$\frac{d}{d\xi}(\ln(E_r/E_i))=0$$

or

$$E_i=c_1E_r, \tag{7}$$

where c_1 is some real arbitrary constant.

Equation (5a) may be now expressed as

$$\frac{d^2E_r}{d\xi^2}-\xi E_r+((\omega L/c)^{2/3}+\xi)(1-\exp-\alpha_1E_r^2)E_r=0, \tag{8}$$

where

$$\alpha_1=\alpha(1+c_1^2).$$

In the over-dense region of the plasma ($\xi\gg 1$) the field of the laser damps out severely and nonlinear term can be ignored. The resulting wave equation is an Airy equation, whose solution may be written as

$$E_r=c_3A_i(\xi);\quad \xi\gg 1. \tag{9}$$

For lower values of ξ i.e., around resonance and in the low density region of the plasma equation (8) needs to be solved numerically On defining $\alpha_1^{\frac{1}{2}}E_r=\psi$ equations (8) and (9) give

$$\frac{d^2\psi}{d\xi^2}-\xi\psi+\left(\left(\frac{\omega L}{c}\right)^{2/3}+\xi\right)(1-\exp-\psi^2)\psi=0. \tag{10}$$

In order to solve equation (10) we have assumed a value of C_3 and used ψ and $d\psi/d\xi$ (as given by equation (9) at $\xi=4$ (say) as the initial conditions. Then employing the Taylor series expansion or Runge Kutta technique, the value of ψ for lower value of ξ are calculated. Knowing the value of ψ (the electric field) much below the critical layer the power of the incident beam can be calculated. The same calculations can be repeated for different values of C_3, i.e , for different values of incident beam power. Here we have carried out the calculations for a CO_2 laser (10·6 μm) incident on a plasma with density scale length $L = 100$ μm plasma temperature 5 KeV and laser powers of the order of 10^{13} watts/cm^2.

Figure 1 shows the variation of electric field of the laser (which is the superposition of forward going and backward coming waves) as a function of distance of propagation In the vicinity of reflection layer the amplitude of the wave

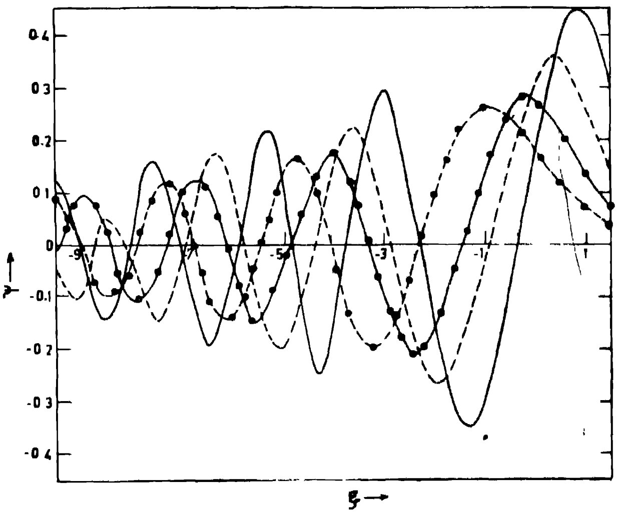

Figure 1. The variation of the electric field of the laser as a function of distance of propagation (ξ) in the plasma for $\omega = 2\times10^{14}$ rad/sec., $L = 100$ μm and power density = 2×10^{13} W/cm^2 (—), 10^{13} W/cm^2 (— — ---), 8×10^{12} W/cm^2 (O-O-O-) and 10^{11} W/cm^2 (- - O - - O - -)

is very high and hence the nonlinear effects are most effective. Due to nonlinear effects the maximum of electric field intensity is shifted towards the region of high density i.e., the reflection layer is pushed deeper into the plasma. Also the characteristic length of intensity variation is reduced (though less pronounced) due to nonlinear effects. Figure 2 shows the variation of modified electron density as a function of distance of propagation. Near the critical layer, the density cavities with sharp gradients are formed. These density cavities would greatly influence the parametric decay process by trapping the decay waves inside them. The sharp density gradients would also influence the resonance absorption (Piliya 1966) of the laser radiation if the latter is obliquely incident on the plasma.

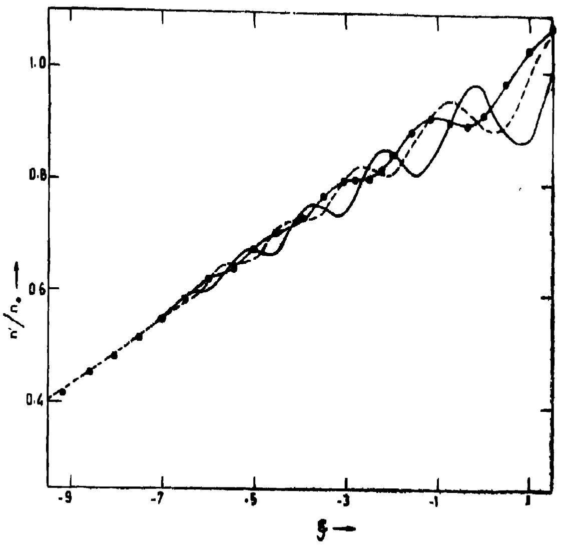

Figure 2. The variation of modified electron density as a function of distance of propagation (ξ) for the same parameters as in Figure 1.

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